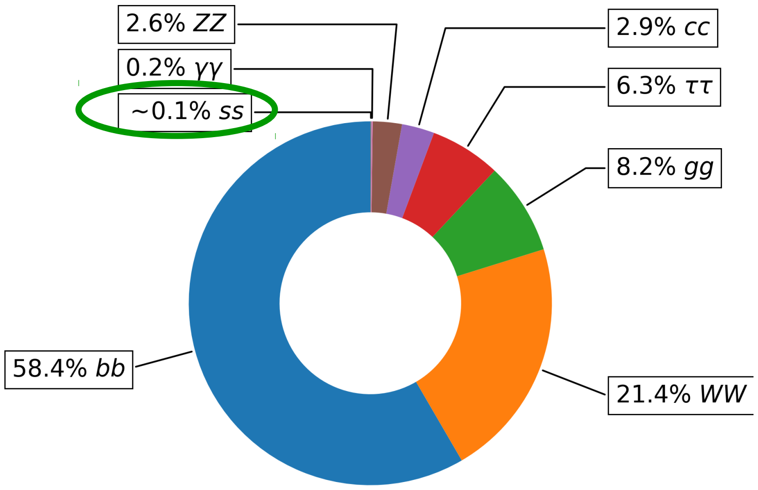
Strange quark tagging with ILD to search for new physics in the Higgs sector

International Workshop on Future Linear Colliders
March 15-18, 2021
PD3: Physics Analyses Session – March 18, 2021

Presented by **Matthew Basso** (University of Toronto),
on behalf of everyone on the **Snowmass 2021 LoI**
and the **ILD Collaboration**

Overview

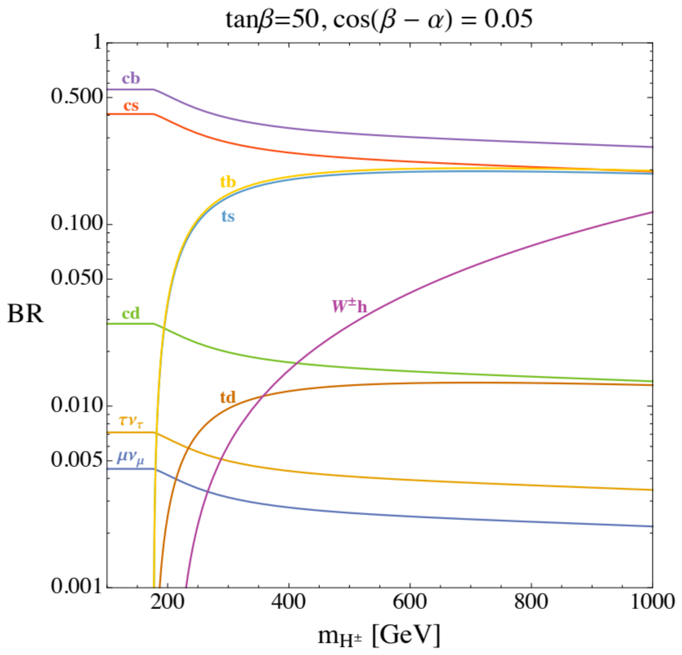
- Submitted a Letter of Interest as part of Snowmass 2021
  - Basic goal: develop a strange tagger using ILD@ILC and apply the tagger to a simple SM $H \to ss$ or BSM $H \to cs$ analysis
    - In line with ILC Snowmass 2021 study questions (2007.03650)
    - Interplay with the instrumentation: strange tagging capabilities strongly depend on the detector (e.g., PID)
  - Collaboration between SLAC, Brown, Oregon, KEK, and Toronto



$\sqrt{s}$ = 13 TeV, m_H = 125 GeV

$H \to ss$ and $H \to cs$

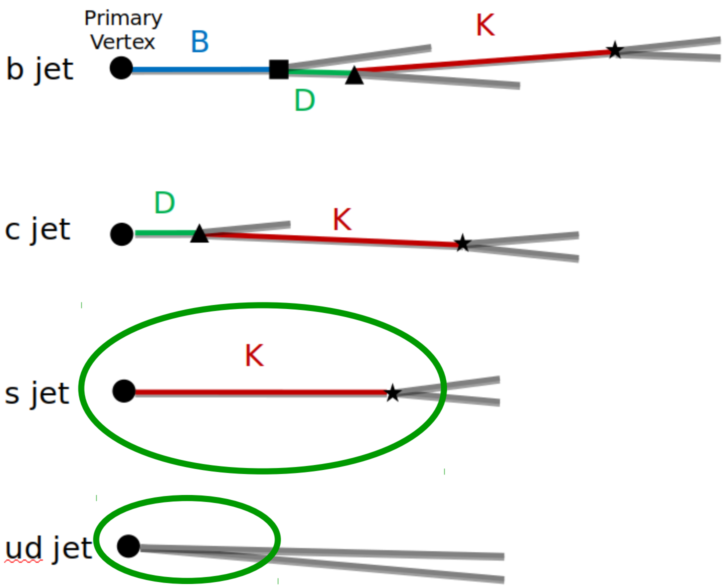
- $H \to ss$: likely to remain out of experimental reach unless enhanced relative to SM expectations
- $H \to cs$: some BSM models allow for the 1st & 2nd generation fermion masses to be an additional source of EW symmetry breaking, resulting in a "SM" Higgs doublet (125 GeV) and a "heavy" Higgs doublet
  - See 1610.02398 for instance
  - Predicts an ***enhancement*** to Higgs cross section
  - Charged heavy Higgs can undergo flavour violating decays (e.g., *cs*) – *s*/*c*-tagging can help here



Charged heavy Higgs branching ratios. Taken from Fig. 6 of 1610.02398.

Different jet types, pictorially

Discriminants



Charged Kaon track

- Zero track impact parameter w.r.t. primary vertex
- Momentum fraction relative to the jet momentum carried by the leading Kaon
  - (Longitudinal vs transverse components?)

V^0 (K_S^0,Λ^0)

- Vertex momentum & displacement must point in the same direction
- Mean vertex distance smaller compared to b/c

+ the usual b/c discriminants (vertex mass, impact parameter for all tracks, etc.)

Remember to normalize the discriminants to make them boost invariant (as much as possible)

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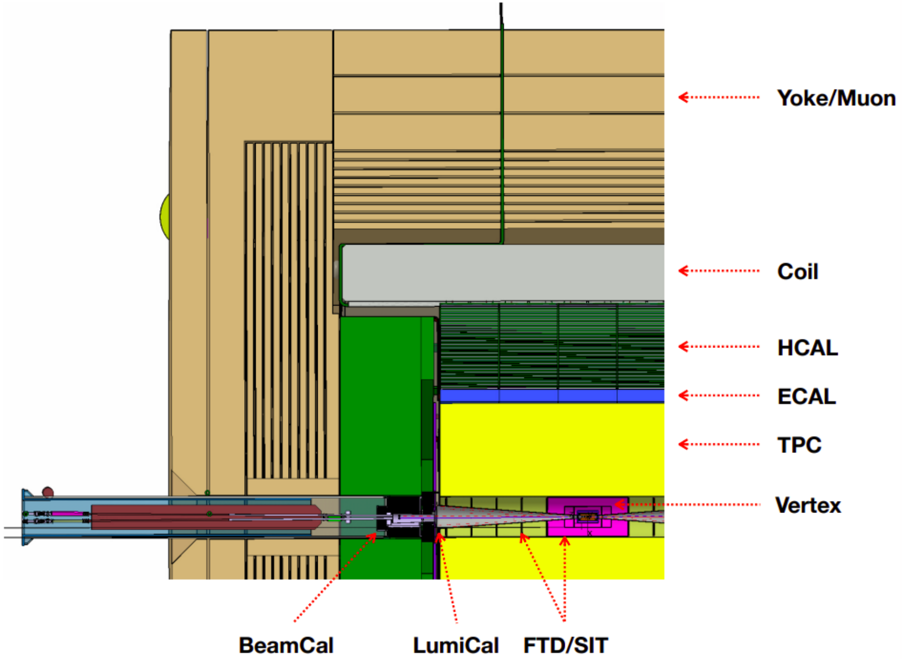
Taken from Slide 5 of Tomohiko Tanabe's 2020/11/24 presentation.

ILD@ILC

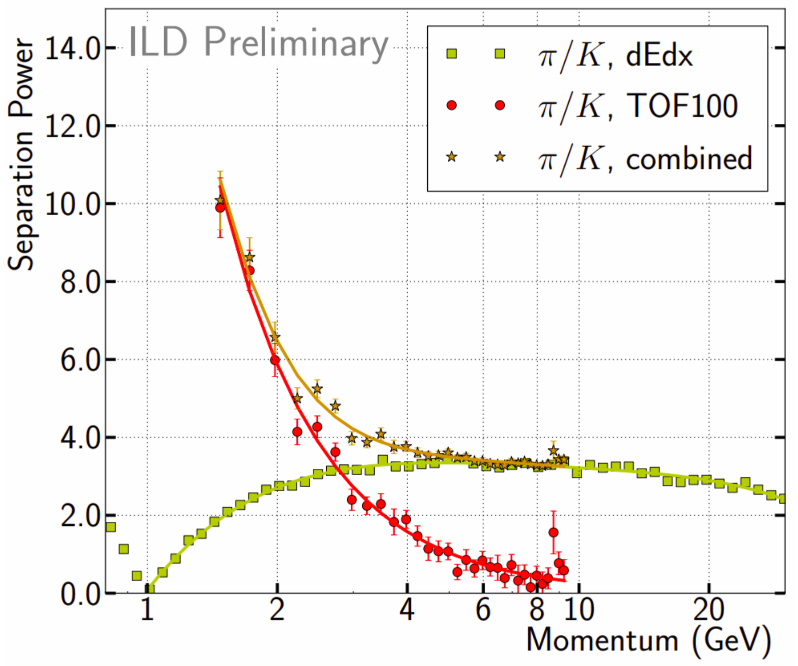
- The ILD detector
  - Detector overview: 1912.04601
  - 3 double-layer pixel detectors for vertexing
  - Time projection chamber (TPC) for tracking with inner/outer Si layers
    - Low material assists in low-*p* tracking
  - High granularity sampling calorimeters for particle flow reconstruction
    - Challenge is reconstructing neutral hadrons
    - Precise EM/hadronic design still under study
  - Tracking/calorimetry contained in 3.5 T field



ILD detector quadrant. Taken from Fig. 1 of 1912.04601.

Flavour tagging requirements

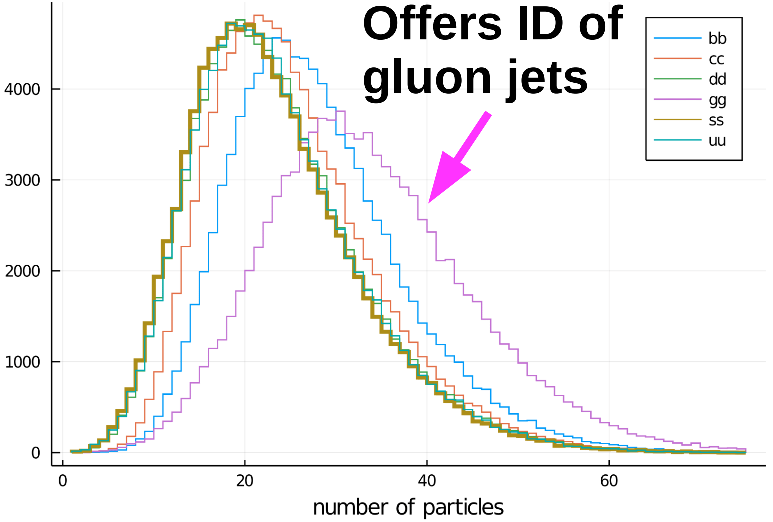
- Good impact parameter resolution, secondary vertexing
  - Pertinent to *b*/*c*-tagging
- For strange versus up/down ("light") quark tagging, there's a need for **kaon tagging**
  - TPC provides *dE*/*dx*, Si detectors on either side of TPC provide time-of-flight (TOF) measurement
  - TOF works best at low *p* (< 10 GeV), expect *dE*/*dx* to work better for kaon tagging (where *p* > 10 GeV)
- ILD already provides BDT scores for *b*/*c*-taggers and an other ("*o*") tagger per jet – these can be utilized



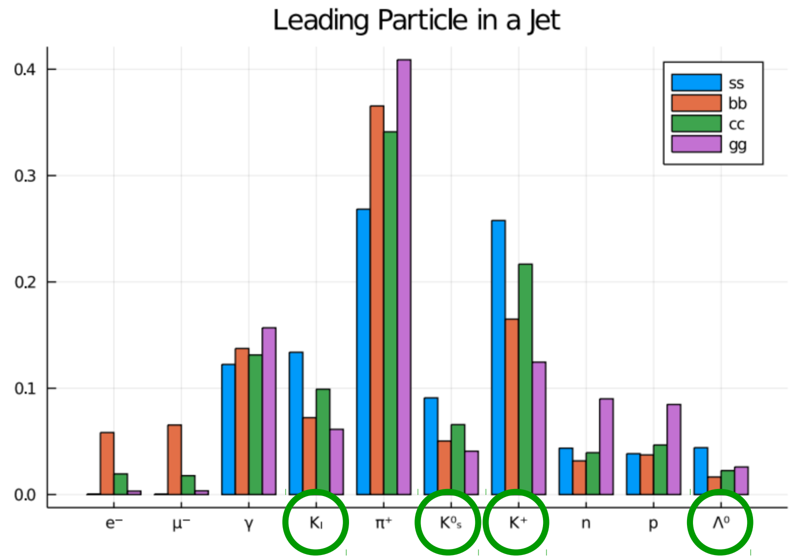
ILD separation power for pions and kaons using dE/dx and TOF (100 ps resolution). Taken from Fig. 3 of 1912.04601.

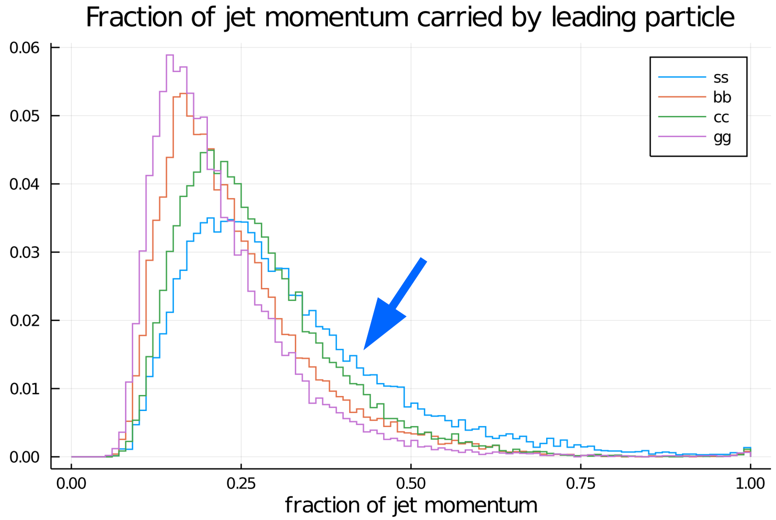
Truth-level $H\rightarrow$hadronic

- Leading particle in strange jets carries larger fraction of jet's momentum
  - Strange particles also tend to lead in $H\rightarrow ss$ events



Plots are *per-jet*





Plots taken from Jan Strube's 2020/11/24 presentation.

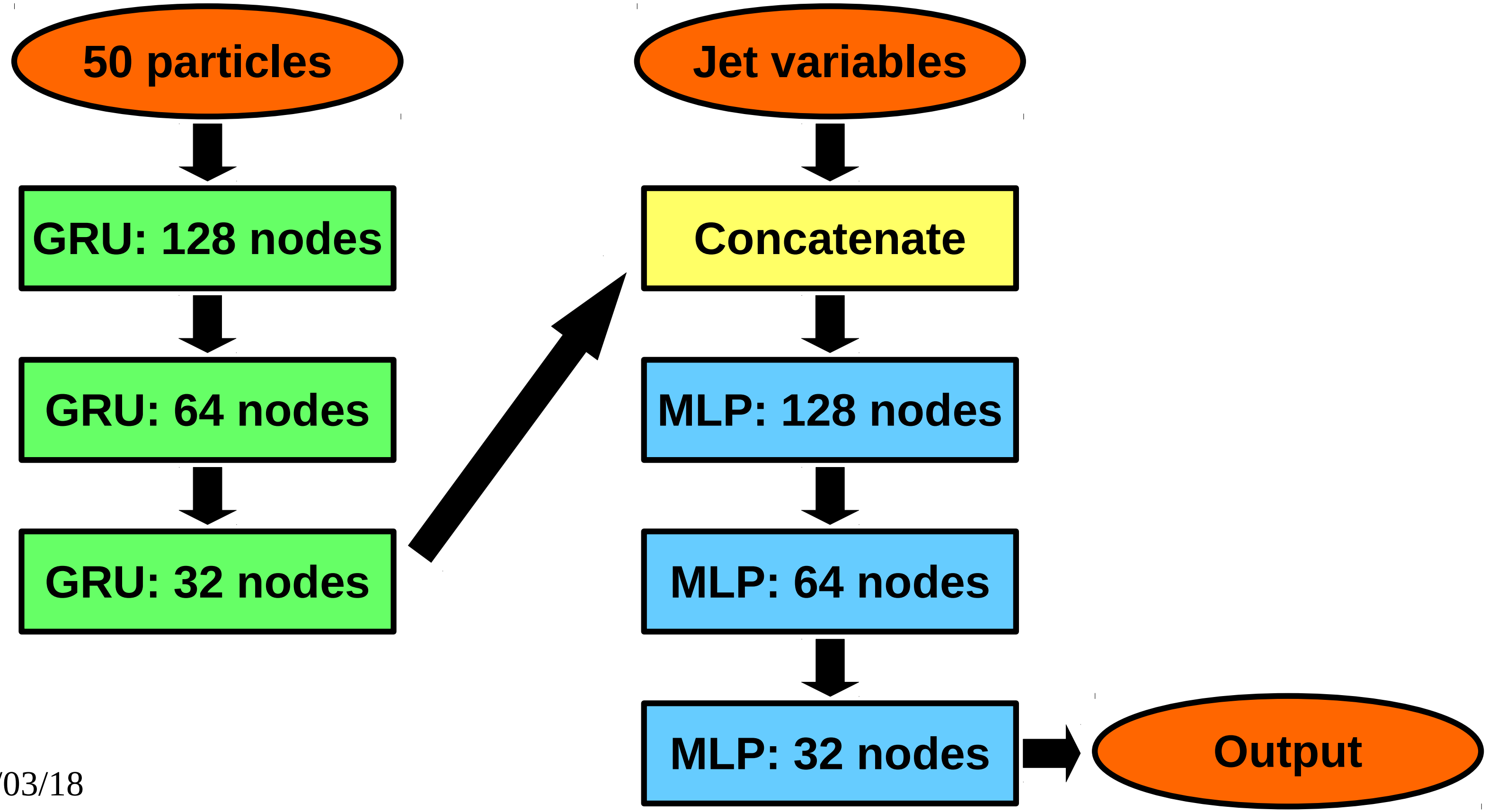
Multiclassifier tagger and inputs

- Use a *multiclassifier* tagger which assigns probabilities to the possible flavours of a jet simultaneously
  - Departure from binary classifiers which assign a probability of a jet having flavour *X* and *not* having flavour *X*
- Train on ILD-reconstructed $H \rightarrow qq/gg$ samples ($qq = uu$, dd, ss, cc, bb) with $\sqrt{s}$ = 250 GeV and $P_L[e^-]$ = 100% and $P_R[e^+]$ = 100%
- Use per-jet level inputs as well as variables on the 50 leading particles in each jet (with kinematics re-defined relative to the jet axis and re-normalized relative to jet momentum)
  - Jets: momentum p, pseudorapidity η, polar angle ϕ, mass m, b/c-tagger scores, $N_{particles}$
  - Particles (tracks): p, η, ϕ, m, charge, number of associated tracks/clusters

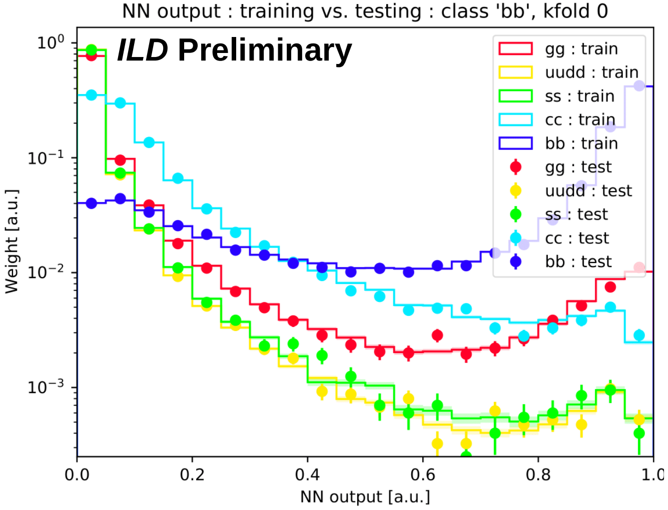
Tagger architecture

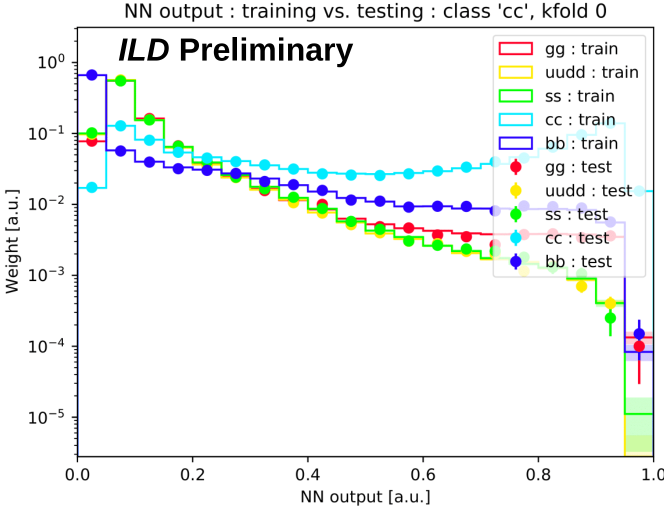
- Looking into different tagger architectures (*more on this*) using neural networks (NNs), but we picked a relatively simple one to start with
  - 3 layer (128→64→32 nodes) recurrent neural network (using gated recurrent units) for particle-level inputs – then concatenated with jet-level inputs and fed into a 3 layer (128→64→32 nodes) multilayer perceptron
  - Architecture shows up in many different HEP measurement scenarios (e.g., recent ATLAS $H \to ZZ \to 4\ell$ couplings measurement, see Section 5.2 of 2004.03447); specifically, applied even to strange tagging performance at **hadron** colliders (used LSTMs instead of GRUs)
    - “Maximum performance of strange-jet tagging at hadron colliders” (2011.10736)

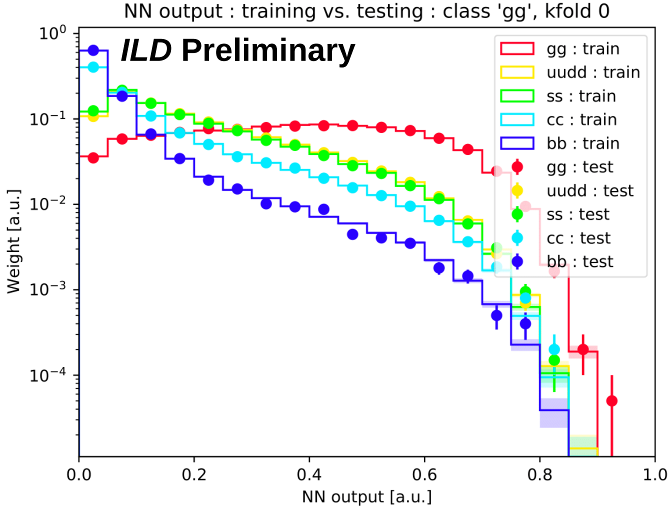
Tagger architecture: pictorially



Performance: *b*, *c*, and *g* jets

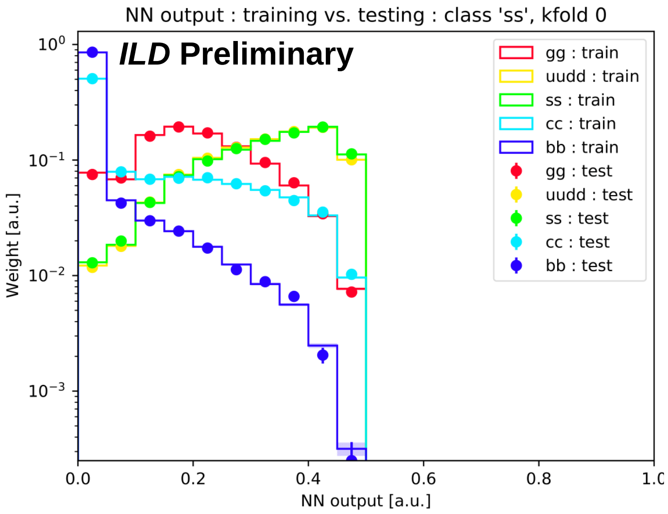


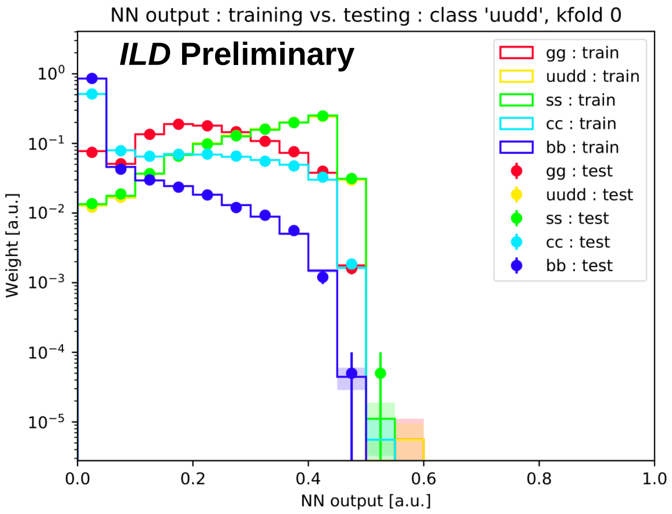




- MVA likely returning *b*/*c*-tagger scores – should do just as well or better than input BDT scores
- **Reasonable** discrimination of gluon jets – likely comes from $N_{\text{particles}}$ input

Performance: *s* and *u*/*d* jets





- Unfortunately, separation of strange and light jets is very **hard** (even p_{lead}/p_{jet} track each other quite closely for these classes)!
- <u>Currently</u>: reasonable separation possible for *b*, *c*, *g*, and *s*+*u*/*d*

Discussion

- What can be done about the strange/light separation?
  - Have yet to utilize *dE*/*dx*+TOF likelihood info for kaon/pion separation – available and inclusion is in-progress
  - Addition of impact parameters per-particle in a jet and the variables used by the BDT *b*/*c*/*o*-taggers (“LCFIPlus”) is also in-progress
- Architecture we intend to compare against current benchmark: “ParticleNet: Jet Tagging via Particle Clouds” (1902.08570)
  - Proposed for flavour tagging at FCC-ee (see talk here)
    - Shows promise for charm tagging – training will likely require a GPU, however
  - Represent particles in jet as a graph and apply EdgeConv (1801.07829) units to relationships between a given particle and its nearest neighbours

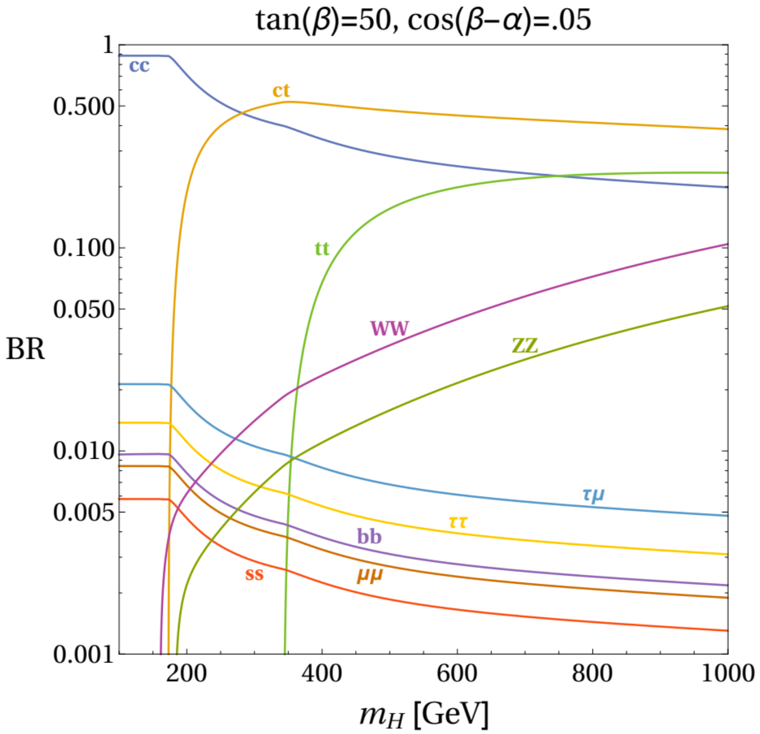
Summary

- Steady progress has been made, but there still needs to be further exploration of PID inputs and NN architectures to achieve strange/light separation
  - A bit of an in-progress report – expect a more complete picture to be ready by Fall 2021 LCWS
- Related study: we are also interested in identifying the detector technology required for strange tagging via simulation

Questions?

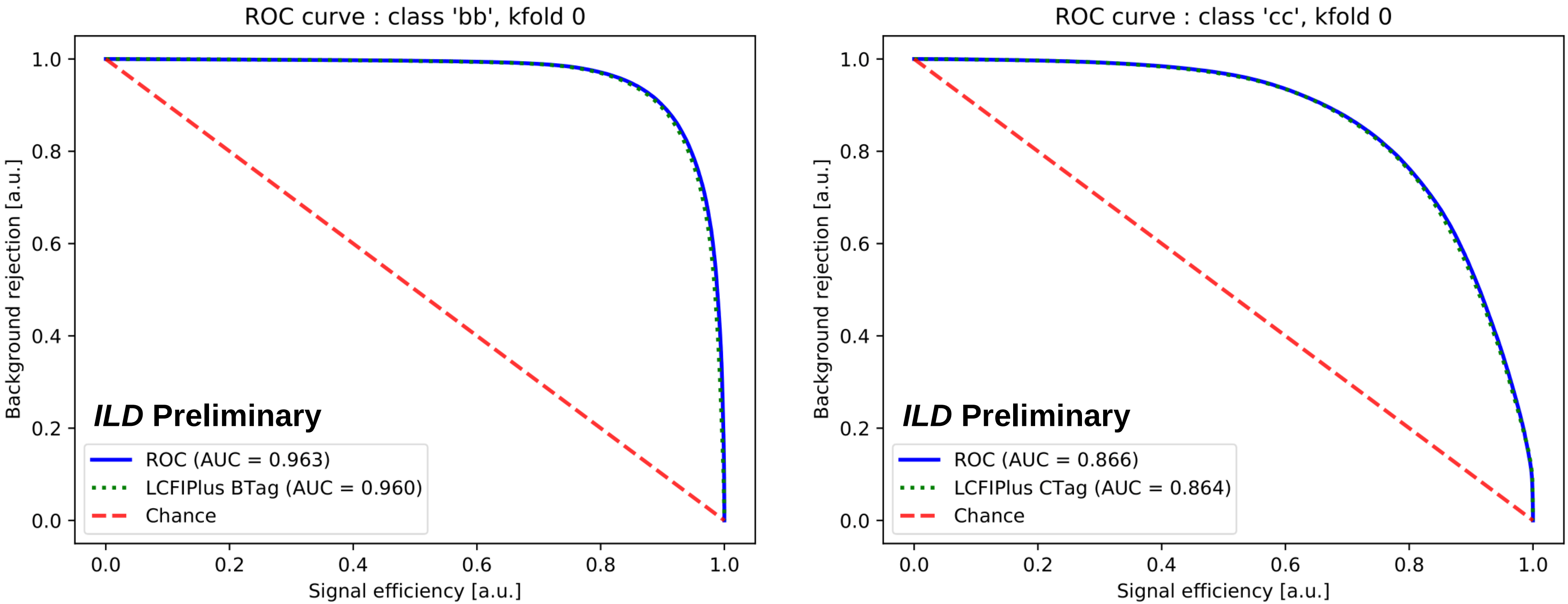
Backup

Neutral heavy Higgs BRs

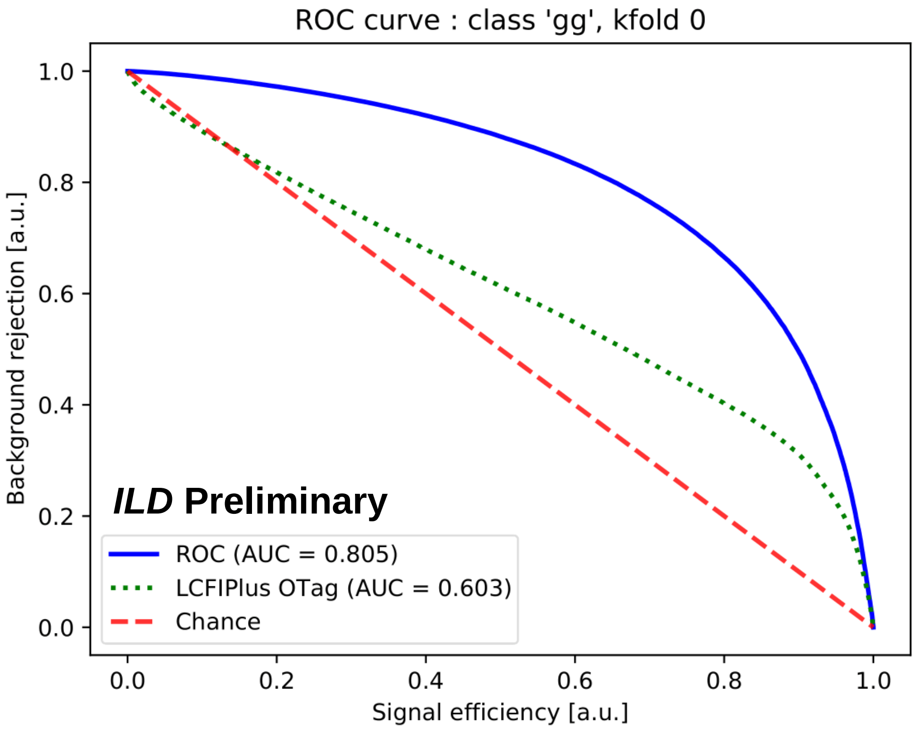


Neutral heavy Higgs branching ratios. Taken from Fig. 3 of 1610.02398.

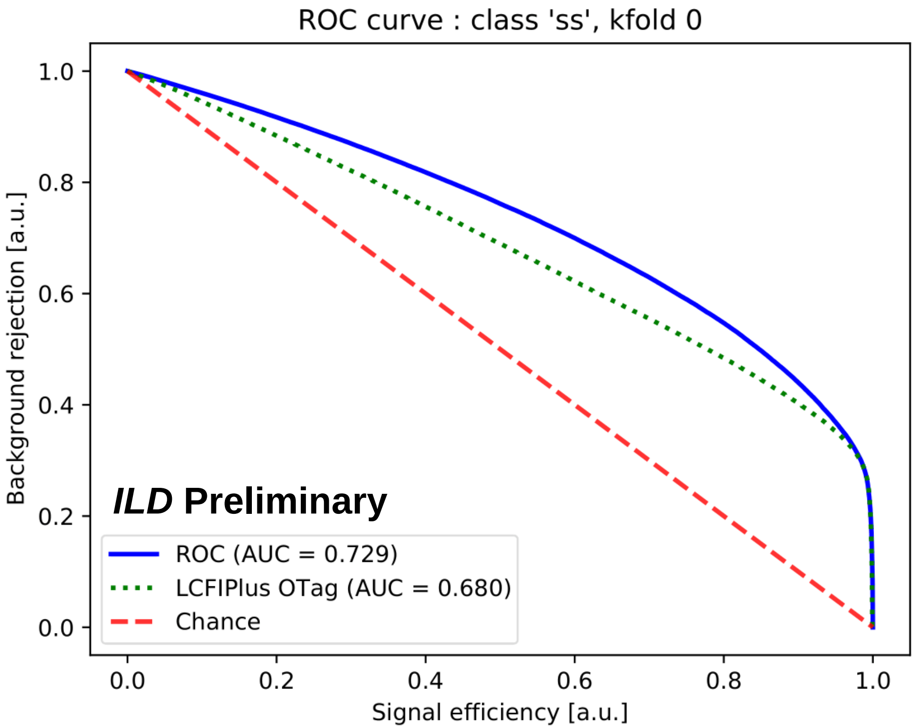
ROC curves: *b* and *c* jets

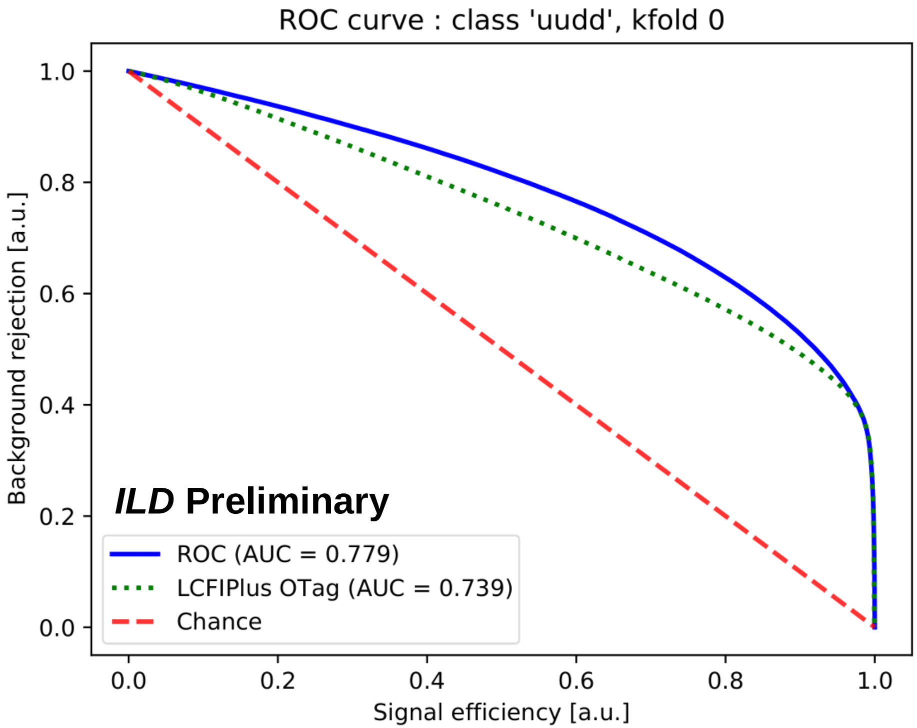


ROC curves: *g* jets



ROC curves: s and *u/d* jets





Multiclassifier confusion matrix